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EVOLUTION OF SURFACE EFFECT SHIP SEAL STRUCTURES AND MATERIALS.(U)
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EVOLUTION OF SURFACE EFFECT SHIP SEAL STRUCTURES AND MATERIALS

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19TH ANNUAL TECHNICAL SYMPOSIUM 1982

ASSOCIATION OF SCIENTISTS AND ENGINEERS OF
THE NAVAL SEA SYSTEMS COMMAND
DEPARTMENT OF THE NAVY – WASHINGTON, D.C. 20360

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EVOLUTION
OF
SURFACE EFFECT SHIP (SES) BOW SEALS

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January 1982

The views expressed herein are the personal opinions of the authors and are not necessarily the official views of the Department of Defense or of the Department of the Navy

ABSTRACT

U. S. NAVY DEVELOPMENT OF SURFACE EFFECT SHIP
SEAL STRUCTURES AND MATERIAL

This paper discusses the important steps in the development of seal and seal materials for Surface Effect Ships (SES) that have been undertaken by the U. S. Navy for the past 15 years. The paper concentrates on bow seals because they operate in a more severe environment than do stern seals and have required significantly more development. The need for this was due also to the large increases in size and speed of the SES being considered by the U. S. over existing SES and hovercraft. These increases introduced the need for new designs and/or seal materials to insure that the larger contemplated seal structures would be lightweight and efficiently perform their sealing functions.

The paper describes various designs that can be placed in two main categories, Flexible Seals and Semi-Flexible Seals. The former are typified by what are known as bag-and-finger seals as installed on the SES100B; the latter are typified by the planing seal proposed for the 3000-ton SES. The advantages and disadvantages of these various designs are discussed and a new design based on theory, previous practical experience and laboratory studies is described. This seal called "Transversely Supported Membrane" (TSM) Seal is currently undergoing evaluation on a U. S. Navy testcraft.

The paper then summarizes the extensive seal materials test and evaluation programs that were undertaken both solely by SESPO and by joint programs with the Navy ACV community. These programs were directed largely towards improving the strength and wear resistance of bag-and-finger materials.

Studies of finger motions on the SES100B and on a towing tank test rig indicated that finger tips may experience accelerations in the 6000-8000 "g" range. The intensity and frequency of these accelerations are related to craft speed, cushion pressure and mass and stiffness of finger material.

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BOW SEALS

1. INTRODUCTION

1.1 Background

Seals or skirts, as they are also known, together with fans are the characteristic components of Air Cushion Vehicles (ACV) and Surface Effect Ships (SES) that differentiate them from conventional ships.

Generally the term ACV is used for craft that contain the supportive air cushion by means of flexible skirts that extend around the full periphery of the hull. SES refers to the type of craft that contain the air cushion by means of rigid sidehulls that are partly immersed in the water and by flexible bow and stern seals. The flexible skirt arrangement give ACV's amphibious capability. The rigid sidewalls of the SES do not permit this capability (although beaching is possible) but on the other hand provide better maneuvering and control and allow water propulsion, either waterjet or propellors, that is potentially more efficient than air propulsion.

1.2 Bow Seal Functions

Bow seals as well as stern seals have one essential function, that of containing the air in the cushion by conforming to the contour of the wave with minimum hydrodynamic drag. This requires that the seal readily "rides" the waves, i.e., that the seal be lightweight with minimum inertia. Such a seal will perform well on the front of the wave because under normal design conditions the dynamic pressure from the water, tending to deflect the seal from the wave surface, is usually considerably higher than the cushion pressure tending to force the seal down onto the water. On the back of the wave, however, particularly at high wave encounter frequencies, the cushion pressure may not be sufficient to force the seal to follow the rapidly receeding wave surface. This causes formation of an air gap which opens and closes with each wave encounter. The resulting air leakage will increase the fan power requirements. If the seal can respond with sufficient rapidity on the down slope of the wave so as to prevent an air gap, it may also tend to "dig in" on the upside of the wave with resulting drag. Seal design, therefore, involves some compromise between these conflicting requirements.

Bow seals can also be designed to contribute towards pitch stability. On SES, pitch stability is largely provided by the sidewalls but in some designs the sidewall contribution may not be sufficient and the bow seal is then designed to contribute towards pitch stability. In this case the seal may require additional stiffness over and above that required for simple sealing with some drag penalty depending on the type of seal used.

Finally, bow seals that are equipped with bags alleviate slamming loads and pressures during cushionborne operations in high sea states. Of the three stated functions, i.e., air containment, pitch stability and slam alleviation, all seal designs incorporate the first and second to varying degrees. The third is incorporated in most designs but may not be included in small craft largely for reasons of simplicity and economy.

Overall, seals must be made as light as possible to minimize air leakage and weight, while at the same time be strong and durable enough to perform reliably in high speed and wave environment.

It should be noted that to date there has been considerable success in combining the various bow seal functions with adequate structural strength and low weight; extensive worldwide use of SES and ACV, testifies to this. However, these seals have been of the bag and finger type, fabricated from flexible elastomer coated nylon fabric, and the craft involved are relatively small, not exceeding 100 tons nominal weight and speeds not exceeding 40 knots (notable exceptions speedwise are the two U.S. Navy testcraft, SES 100A and B, the latter achieving a speed in excess of 100 mph). Recent research, i.e., Ref. 1 indicates that with increasing weight and speed, finger wear tend to limit seal life and there has been a need to overcome this problem. Furthermore, recent SES developments show the need for seal retraction and stowage during hullborne operations and some recent and current seal designs address these requirements. These various designs will be discussed in this paper.

Only bow seals are discussed, since compared to stern seals, they represent a more challenging problem. This is because, with a proper rear seal design as shown in Fig. 1, the cushion pressure tends to force the seal away from the water surface. It is relatively simple to apply a counter pressure so that in calm water a rear seal will remain in equilibrium under the action of largely aerostatic forces, hydrodynamic forces being of secondary importance. With bow seal designs, the cushion pressure tends to force the seal onto the water surface but it is not possible to supply a counter pressure as can be done with rear seals. The bow seal equilibrium is achieved as a result of a combined action of aerostatic and hydrodynamic forces and restraints built into the seal structure, e.g., tension straps. This makes bow seal design more difficult than that of the rear seal. In the U.S., therefore, most SES seal development effort has been devoted to the bow seal.

There are two basic types of seal that have been studied in some depth in the U.S. Navy as being potential candidates for seal design in that they appear to have satisfied the desired characteristics. These two basic types are:

- o flexible
- o semiflexible

In the early development of SES, rigid seals had been studied but it was soon found that they did not respond to waves in a satisfactory manner,

thus eliminating these seals from further consideration. Flexible and semiflexible seals are discussed below.

2. Types of Seals

2.1 Flexible Seals

These are represented by what are known as Bag-and-Finger seals shown conceptually in Fig. 2. The seal consists of a bag attached to the bow structure that is inflated by means of fans to a bag pressure somewhat greater than cushion pressure (5-25% higher depending on the design). Open fingers are attached to the bottom of the bag and to the wet deck. The portion of the fingers above the waterline when inflated, appear from ahead as semi-cylinders. The bag may be in the form of a semi-torus ("3D") or in the form of a cylinder ("2D") depending on the overall SES design. In some designs, the bag is eliminated and the fingers attach totally to the wet deck. Also closed fingers can be used.

For the size and speed of operation of existing SES using the bag and finger bow seal, the fingers conform very well to the wave surface with acceptable low drag. In general, finger conformance is a function of $\frac{\rho v^2}{2p}$ when p = finger inflation pressure, ρ = water density and v = forward speed. When $\frac{\rho v^2}{2p}$ exceeds unity (approximately) the submerged portion of the fingers will be deflected up to the water surface by dynamic action. Considering the SES100B, p = 100 psf and at a typical operating speed of 50 knots $\frac{\rho v^2}{2p}$ is 71·4 indicating very rapid finger response. At low speeds, say 6 knots or less, the fingers would tend to remain undeflected and would "drag" through the water. The upper part of the seal, i.e., the bag, is less responsive than the fingers and therefore generates high drag when impacted by the water. The finger height, therefore, is selected so that bag impact will be minimized up to some specified sea state as determined from operational requirements. Overriding this consideration is the need for adequate bag size for slam alleviation in high sea state. Thus finger height selection is a trade off between hydrodynamic drag that affects powering, speed and range and between slam force that affects structural weight and, therefore for a given range, payload.

Fingers have the advantage that they provide a pitch restoring mechanism. This is seen in Fig. 3 that shows diagrammatically the effect of a bow down trim Θ on the finger. The finger at the water surface is buckled so that there is an effective increase of cushion area ΔA given by $\Sigma B \times \Delta L$ where B is the finger width and ΔL is the increase in cushion length. This results in a forward shift of the center of pressure on the cushion and a corresponding increase in pitch restoring moment.

It may be observed that the magnitude of the increased area is a function of finger rake angle ϕ, A increasing with ϕ, i.e., pitch restoring moment increases with ϕ. There is, however, a limiting maximum value for ϕ because of finger stability considerations. Finger stability is determined by cushion pressure, ship speed and finger geometry (width height and rake angle) and is described more fully in Ref. 2.

The bag provides an important function in opposing hard structure slamming although this advantage applies to any seal type that incorporates a bag in its design. During slamming conditions, the fingers and most of the bag are fully wetted and the pitch restoring function is primarily provided by the buoyancy forces produced by the bag as shown in Fig. 4. Fig. 5 taken from Ref. 3 shows the effectiveness of the bag in reducing hull loads. The magnitude of these forces is determined by the bag volume, bag pressure lift fan characteristic and the area of the bag openings. The effect of the latter is illustrated in Fig. 6. With very large openings, the bag collapses too quickly and is incapable in reducing the closing velocity at the bow to prevent hard structure slamming. However, if the openings are too small, large bag pressures will develop, causing high stresses in the bag material. Likewise, a larger volume bag provides more "travel" distance than smaller volume version and therefore are more effective in alleviating slamming. However, increase in volume requires larger in bag radii. Since stresses in the bag material are a function of a product of bag pressure times the radius, bag size is limited by the ability of bag material to withstand these stresses. Fig. 7 shows typical bag pressure time histories obtained during rough water trials of the SES100B testcraft.

Some special features of different types of flexible seals that have been used in U.S. Navy projects are described below.

2.1.1 Toroidal Bag and Finger Seal ("3D")

Fig. 8 shows a design of this type of bow seal that was developed by Bell Textron for the 3KSES (Ref. 4). This seal was never built but a smaller version was extensively tested on the SES100B. Similar seals exist on hovercraft such as those built by British Hovercraft Company and on SES such as the Hovermarine HM-2. The justification for this configuration is that better yaw stability can be achieved by shortening the length of the sidehulls. With shorter sidehulls, relative to full length sidehulls, the hydrodynamic sideforce is reduced and the center of pressure is shifted aft causing a reduction in the moment arm, and therefore the destabilizing moment. This arrangement reduces the required fin and/or rudder area and decreases the drag and draft of the craft.

These advantages of "3D" seal configuration are offset by difficulties of fabricating toroidal bag shape and complexities of construction and maintenance of the fingers, because the finger geometry depends on finger position relative to the craft so that two fingers are alike.

The toroidal shape also produces difficulties with the vertical seams which join the bag segments, because the double curvature surface, causes the seal to develop stresses in axial (horizontal) as well as hoop (vertical) directions as shown in Fig. 9. The axial forces produce tensile stresses in the seams which are transmitted from one segment to another via coatings and adhesives. Because adhesive strength is considerably less than the strength of the reinforced fabric, bag size is limited by the strength of bonded seams. Although seams with up to 5000 lbs per linear inch (pli) have been developed, these seams have large overlap area and are quite stiff. High bending stiffness in bag seams may result in excessive seal maintenance because of flexural fatigue damage to seam material.

2.2 Cylindrical Bag and Finger Seal

As shown in Fig. 10, that was extracted from Ref. 5, the seal arrangement is, in principle, similar to "3D" seal except the toroidal bag is replaced with a cylindrical bag of which the two ends are contained by the sidehulls. This considerably simplifies the bag design. The sidehulls act as end closures for the bag and absorb the axial stresses so that this seal, unlike the "3D" seal, does not require high strength seams. The finger design and maintenance are also greatly simplified, because all the seal fingers are symmetrical and fully interchangeable.

Compared with the "3D" seal, this type of seal is no longer size limited because of limitations in seam strength. The constraining factor becomes the maximum tensile strength of commercially available materials which is currently in 4-5000 pli range but this constraint may be circumvented by using a multi-loop bag geometry such as shown in Fig. 11; the number of loops are dictated by the seal size and bag pressures. The loops reduce the local bag radius so that the tensile stress which is a product of the radius and bag pressure will remain within the material strength allowable.

2.1.3 Finger Seals

The all-finger seal is illustrated in Fig. 12. This seal is very simple and easy to maintain. Since there is no bow bag, hard structure alamming will occur on occasions during on-cushion operation because in large waves, once the fingers are fully deflected, the wave can hit the bow ramp or knuckle. This defect can be partly overcome by combining the seal design with large volume "buoyancy" sidehulls which can provide large pitch restoring moments. These would tend to lift the bow in large waves therefore preventing hard structure contacts. A seal of this type is presently installed on SES110 craft. The all-finger seal is not practical for large SES in excess of 1000-ton displacement because the fingers become too large and unwieldly and their replacement costly.

2.2 Semi-Flexible Seals

This type of seal is shown conceptually in Fig. 13. It consists of an upper flexible bag and a lower planing element that may be rigid or semi-flexible with a restraint cable or cables to support the lower element against the internal cushion pressure. Originally, the purpose of this design was two-fold. Firstly, by using planing elements instead of flexible fingers, the seal was intended to provide a more positive pitching restoring moment than would be obtained with fingers. Secondly, the planers were intended to reduce seal wear at the water surface due to flagellation. This topic is discussed in some detail in Sections 3 and 4, but briefly, flexible fingers experience wear at the finger tips due to whipping motion that requires fingers to be replaced at intervals. For craft of the size and speed built so far the maintenance problem has not been too serious, but would be expected to grow as ship size and speed increases. The designs described below show the different approaches used for designs that were brought to fruition, for reducing or eliminating this potential problem. Many other concepts were studied, e.g., Ref. 6.

2.2.1 Stay-Stiffened Fabric Membrane Seal

This type of bow seal as shown in Fig. 14 was designed and installed in the U.S. Navy XR-1 as well as the SES 100A. As described in Refs. 7 and 8. It consisted of a membrane stiffened by a series of flexible stays equally spaced across the bow, the membrane and the stays being attached by a piano hinge to the hard structure at the top of the bow ramp. Together, the membrane and stays formed a semi-flexible planer that was forced down on to the water surface by means of the bag formed by the fabric loop the stiffened membrane and the bow ramp.

The membrane design considerably reduced flagellation at the water surface. This concept as well as the two planing seals described below are no longer being pursued because of current Navy interest in high length-to-beam ratio ships with high volume sidehulls. With this type of design, the sidehulls provide all the pitch restoring moment required and it is not necessary, therefore, to design the seal to provide this moment. It should also be noted that for this seal and the Fiberglass Membrane Seal, it is an intrinsic feature of the designs that the lower elements have flexibility. There may have been, therefore, a potential problem when scaling to larger sizes in that stiffness tends to increase with size. Although not particularly affecting the design structurally, increased stiffness might have influenced adversely the seal performance in waves causing increased drag and loads.

2.2.2 Single Planer Seal

The seal shown in Fig. 15 was, like the previous one, installed on the XR-1, for evaluation.

This design was a development of the previous design, with the stiffened membrane being replaced by a one-piece fiberglass planing surface designed to resist the hydrodynamic and inertial forces generated by speed and wave impact. The planing surface was supported by two series of straps, retraction straps for vertical retraction on-cushion and geometry straps to overcome the forward force on the seal due to pressure. The lower end of the planer was equipped with "feathers" that consisted of tapered fiberglass panels. The feathers, used because of their assumed high wear resistance, were designed to deflect in small waves so that they could ride the wave without requiring motion of the main planing surface. The assumption of high wear resistance was validated by both experience on the boat and by water tests performed in a special test facility developed under 3KSES program Ref. 9. The later experience with SES100A bow seal, indicated that feather life was at least an order of magnitude longer than the finger life under similar conditions.

It should be noted that the bag of this seal as shown in Fig. 16 protrudes forward of the sidewalls making it 3-dimensional. It was originally intended to make the bag 2-dimensional but this was not possible because of the problem of retrofitting this seal to the XR-1 while maintaining the same cushion length as in the previous seal. Had the bag been designed to fit within the sidewalls, the feather tips would have extended much further aft thereby shortening the cushion and changing its drag characteristics. The seal worked effectively on the XR-1 providing the necessary pitch restoring moment but as expected, with some drag penalty. This seal formed the basis for the 3KSES planing seal designed by Rohr Marine and described in the next sestion.

2.2.3 Semi-Flexible Planing Seal (3KSES)

Fig. 17 taken from Reference illustrates the planing bow seal proposed by Rohr Marine, Inc. for the 3KSES. A scaled version of this seal was built and tested on the SES100A craft.

The main features of this seal include:

(1) A "2D" straight across bag similar to that discussed previously.

(2) A set of planers which are joined together by flexible interplaner joints. Each planer is supported by flexible stays in the front, a "geometry" strap in the middle and a "retract" strap at the lower end. The latter is connected to a retract mechanism which permits the vertical adjustment of the seal during on-cushion operations. During off-cushion operations the seal can be fully retracted and stowed. The lower end of each planer is equipped with a "feather" similar to the seal installed in the XR-1.

Each planer represents a wide beam structure designed to resist hydrodynamic and inertial loads generated by high-speed and wave impact environment. The major drawback of this seal is its relatively high weight. Compared with a similar bag and finger seal, the weight of 3KSES scale planing seal was approximately three times greater. The planers constitute the major fraction of the seal weight, their weight being dictated by the required strength of the planer structure to overcome the effects of, wave slamming and snap-back. The latter effect consists of planers being arrested suddenly by the straps during their downward motion after being lifted and dropped by a wave action. The loads are functions of cushion pressure, planer's weight, strap elasticity, the distance between strap supports and the width of the planer.

The addition of further straps in the fore-and-aft and athwartship directions could reduce loads and therefore planer weight but this solution would greatly increase the complexity of planer design. Also since it is not possible to insure uniform strap elongation, the loads in a multi-span planer will vary depending on the extent of individual strap support. This adds further complications to seal design.

2.2.4 Transversely Supported Membrane (TSM) Seal

The TSM seal represents an attempt to combine the long wear life characteristic of the planing seal with the lightweight and efficiency of bag and finger seals. Fig. 18 provides an illustration of TMS seal. As shown, therein, the upper portion of the seal is similar to the "2D" bag and finger and planing seal bags.

The distinguishing feature of this seal is the multi-hinged polygonal surface that together with the radial webs form a structure that for

the want of a better name is called the "parasol". This performs the same function as fingers or feathers, i.e., it provides a quick response compliance with wave surface and minimizes air leakage due to wave action.

Each parasol element consists of fabric stiffened by lightweight stiffeners or battens as shown in Fig. 19. The battens perform two functions. Firstly, the battens provide the stiffening and damping necessary to reduce the flagellation motions that have been identified as a primary cause of finger material wear. Comparison of the accelerations measures on SES100B seal finger with those obtained from TSM seal battens tested on XR-1 SES testcraft showed an order-of-magnitude reduction in accelerations. Also, the battens stiffen the parasol sufficiently to enable it to maintain a predetermined geometrical shape.

Structurally, each batten is simply supported beam loaded by cushion pressure and unlike the statically indeterminanant redundant planer structure of the planing seal, the flexural stresses in the batten are not affected by stretching and deformations at the supports. The span of the batten corresponds to the width of the parasol element with the end supports provided by the sides of the loop. By restricting the span to 12-15 inches, the batten thickness is limited to no more than 0.1-0.15 inches of fiberglass material for a ship of the size of the 3KSES, resulting in a lightweight, low-mass element.

Compared to seal fingers, the deformation pattern of the parasol is very orderly and occurs along the well-defined hinge lines formed at the junction of the adjacent elements. This is because the axis of the parasol polygonal is parallel to the water plane, making the parasol conformable to the wave surface. The finger axes in comparison, are at an angle to the water plane, so that the fingers cannot conform to the wave surface without forming three dimensional knuckles and folds. From fatigue standpoint, these local finger folds provide areas of stress concentration and have less resistance to fatigue than the hinge line of the parasol seal.

The TSM seal has been tested extensively in a static test rig (Ref. 12) and in a towing tank (Ref. 13). Seal Design studies for the XR-1 testcraft and for larger ships are described in Refs. 13 and 14. The seal was recently installed on the XR-1 testcraft and is undergoing evaluation.

The seal has exhibited excellent performance characteristics such as low drag, good cushion containment, quick response to wave and good lateral conformance to quartering waves and after 60 hours of testing shows no fabric wear at the seal tip. Recently, the XR-1 craft achieved a speed of 47 knots, which is the record for an SES craft 55 ft long. A second generation seal is now being installed.

One of the improvements suggested by the XR-1 tests was modification of the batten design. The original batten consisted of a thin fiberglass panel the width of which corresponded to the width of the parasol element and the length corresponded to the cushion width of the craft. Under the air pressure, the batten structure deflected

forming a segment of a cylindrical shell, which stiffened the batten transversely and reduced lateral compliance. The bending stresses produced by waves in the athwartship direction caused repeated buckling and excessive local straining of the stiffened batten material resulting in fatigue cracking (with, however, no apparent effect on seal performance). This problem was solved by use of a segmented batten such as shown on Fig. 19. As illustrated therein, the batten is divided transversely into a number of short parallel beams, separated by rubber spacers and bonded to the parasol fabric at the top and bottom. This sandwich arrangement eliminates the stiffening effect of the batten deflection, improves lateral compliance and greatly improves damping and impact resistance.

The TSM seal currently being tested on XR-1 testcraft was successfully fabricated and installed by Navy personnel without prior seal fabrication experience. This fact attests to the simplicity and producibility of this seal. The planing seals installed on SES100A required the involvement of material and structural experts with many years of prior seal development experience.

Stresses in the bag, parasol and batten material may be maintained at the desired level by increasing the number of bag or parasol loops, therefore, the TSM seal is not size-limited. To achieve, however a proper balance between weight, proportions and strength and fatigue performance requirements of the TSM seal, a careful trade-off study will be required.

3. SEAL MATERIALS

With the exception of semi-rigid elements such as battens or planers, which are made from fiber reinforced plastic, seals are made from flexible fabric reinforced elastomers. These materials must have adequate strength, wear and fatigue life and be able to resist the effects of the ambient environment. Strength properties are primarily determined by fabric reinforcement, although coating and adhesives also influence these properties. Nylon fabrics with tensile strength up to 5000 pli have been successfully developed under the 3KSES program, a strength more than adequate to satisfy the bow seal strength requirements for SES's currently contemplated by the Navy, i.e., in 1500-15,000 LT range. Wear and fatigue life requirements present a more difficult problem and because of this, the major portion of seal material development effort has been devoted to improve wear and fatigue resistance of seal materials.

Fig. 20 presents a summary of the factors which affect seal material life; it is seen that the problem is complicated by environmental factors, such as, temperature, water immersion, ozone, etc., which affect strength and fatigue properties of the materials. As can be readily observed, it is virtually impossible to develop a material which represents an optimum compromise between all these factors, nevertheless, as a result of the work by the SES and ACV community, seal material life has improved dramatically, for example, finger life has increased from less than ten hours for early ACV skirts to more than 500 hours for the recently developed SES 110 craft.

The improvement has been due to tests and ranking of a large number of elastomer material formulations with or without fabric reinforcement. Fig. 21 provides an example of some of the variables studied by Goodyear in their work to achieve wear resistant SES finger materials. The details of elastomer and adhesive blends and formulations are provided in Refs. 15, 16, 17 and 18 and are outside the scope of this paper. It is suffice to say that the current seal materials have withstood several years of environmental exposure without serious adverse effects, however, the dominant causes affecting seal life are flagellation and cyclic load effects these are discussed separately in the following section.

4. FLAGELLATION AND CYCLIC LOAD EFFECTS

Cyclic loading is most pronounced in the portions of the seal which are required to operate at air/water interface, e.g., seal fingers. The seal bag experiences relatively few cycles and is therefore less vulnerable to fatigue damage. Existing bags have 4-5000 hours between replacements and longer life is possible with improved care and maintenance. Exceptions to these are stiff highly stressed seam areas of large toroidal bags and hard structure connections which cause seal material to knuckle sharply.

Cyclic loading proved to be a significant factor affecting the design life of the planers of the 3K planing seal. Its occurrence made it difficult to achieve a good balance between minimum weight which dictates higher operational stresses and therefore shorter life, with fatigue requirement which dictates lower operational stresses and therefore higher planer weights.

Most of the flagellation and cyclic loads studies were performed with finger seals. The term "flagellation" applies to high cyclic motions of finger material akin to those of a flag fluttering in the wind. Flagellation occurs in the unstressed lower portion of the finger that has been deformed by wave action at speed and represents a high cycle fatigue phenomena accompanied with hysterisis effects which produce heat build-up at coating/fabric interface and deterioration of tensile and shear strength of the elastomer. In contrast, fatigue loads caused by waves' encounters are a relatively low cycle phenomenon and does not engender significant heat effects. Flagellation damage is typified by cracking and spalling of the coating materials and subsequent unravelling of the fabric and it normally occurs much sooner than flexural fatigue damage caused by wave encounter.

Flagellation motions of seal fingers instrumented with miniature accelerometers, were studied during SES100B sea trials and on a specially designed test rig in the DTNSRDC towing tank. Description of this program is presented in Ref. 1. Some of the interesting results of the tests are reproduced in this paper. The tests revealed surprisingly high accelerations and frequencies. Accelerations measured near the finger tips were in excess of 4000 g's with frequencies approaching 200 Hz. As shown in Fig. 22, accelerations increased with increase in cushion pressure and craft's speed. Test results indicated that acceleration frequencies also increased with speed. The accelerations measured during these tests include the effect of the accelerometer mass. Calculations showed that accelerations of finger material unburdened by the accelerometer weight would probably be double the measured values.

The accelerations were the highest at the finger tip and dropped rapidly as distance from the tip increased, Fig. 23, but acceleration activity was negligible in the vicinity of the folds which tended to stiffen seal material locally and separate it from the water flow. The relationship between accelerometer activity and finger wear was established by a finger wear test in a facility capable of simulating cushion pressure and speed effects, (Ref. 7). The wear test, confirmed by field observations indicated that finger wear rates increase with speed and air pressure and that coating delamination is initiated at the finger tip which is also the area experiencing maximum accelerations.

Calculations indicated that stresses at coating/fabric interface due to inertial effects, even in 8-10,000 "g" environment, is insufficient to cause coating delamination as long as it remains near room temperature. However, the high frequency motions of finger material produce hysteresis in the elastomer which raises its temperature causing a rapid deterioration on the tensile and fatigue strengths of the coatings and adhesives. The tests suggest that the means for improving seal wear resistance depends on operational and micro and macro-structural factors, e.g., elastomer and adhesive compositions, fabric weave geometry, coating thickness, etc.

Decrease in craft's speed and cushion pressure reduce flagellation motions and results in longer wear life. Flagellation requires an intimate contact between seal material and water surface. Tests with instrumented SES100B fingers indicate that flagellation occurs during wave contact and stops when the contact is broken. Indications are that these rest periods allow some heat dissipation in the elastomer and can cause a reduction in wear rates. From the micro-structural standpoint, elastomers with lower hysteresis, e.g., natural rubber, perform better than those with high hysteresis. The tests also suggest that coatings and adhesives with improved heat resistance would result in better seal performance.

Macro-structural aspects of the wear problem encompasses concepts other than fingers, e.g., feathers of planing seal and the battens of the TSM seal. Both these concepts employ mass and stiffness factors which were shown to reduce flagellations and improve wear characteristics of the seal.

A comparison of the batten accelerations measured on XR-1 with those measured on SES100B fingers indicates that the batten accelerations are order-of-magnitude lower than those of a finger. This suggests that TSM seals should have much better wear characteristics than fingered seals. The preliminary test results support the above conclusion. After more than 55 hours of operations at speeds up to 47 knots, the TSM seal parasol installed on the XR-1 testcraft shows no evidence of coating delamination and spalling with typify wear damage.

5. CONCLUSIONS

The salient conclusions based on the above discussions are presented below:

a. Both "2D" finger seals and TSM seals can be designed with an adequate strength margin for all the SESs currently contemplated by the Navy, i.e., in 1500 to 15,000 ton displacement range.

b. "3D" bag and finger and planing seals are size limited. The first because of limited tensile and fatigue strength of the vertical seams in the bag and finger wear, the second because of excessive weight of the planers which must be made strong enough to resist slamming and snap-back loads.

c. Finger wear is caused by high frequency and high acceleration motions in finger material. The accelerations and wear are functons of craft's speed and cushion pressure.

d. Flagellation motions are affected by local mass and stiffness of the flagellating surface, and decrease as these values increase.

e. Elastomer hysterisis plays an important role in finger wear. Heat build-up produced by hysterisis effect reduces tensile and fatigue resistance of adhesives and coatings.

f. Use of GRP planing elements, e.g., feathers or battens, result in an order-of-magnitude improvement in seal wear performance.

g. The TSM seal uses features that derive from both Bag and Finger Seals and Planing Seals. Test of the TSM seal on the XR-1 have shown excellent performance characteristics of the TSM seal and have provided evidence of greatly improved wear life. That this seal was successfully constructed by Navy personnel without any prior seal fabrication experience attests to the simplicity and producibility of the TSM seal concept.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge Bell and RMI personnel whose dedicated work has made SES seal improvements possible. Thanks are extended to Maridyne personnel for designing the XR-1 TSM seal and to SESTF personnel for constructing and instrumenting this seal. Special thanks are extended to Peter Besch of Code 1556, DTNSRDC, for his inventiveness and ingenuity in measuring finger flagellation accelerations which greatly contributed to the understanding of the seal wear phenomena. The authors also appreciate the patience and dedication of Phyllis Sandine and Jady Oliver who typed and corrected the manuscript.

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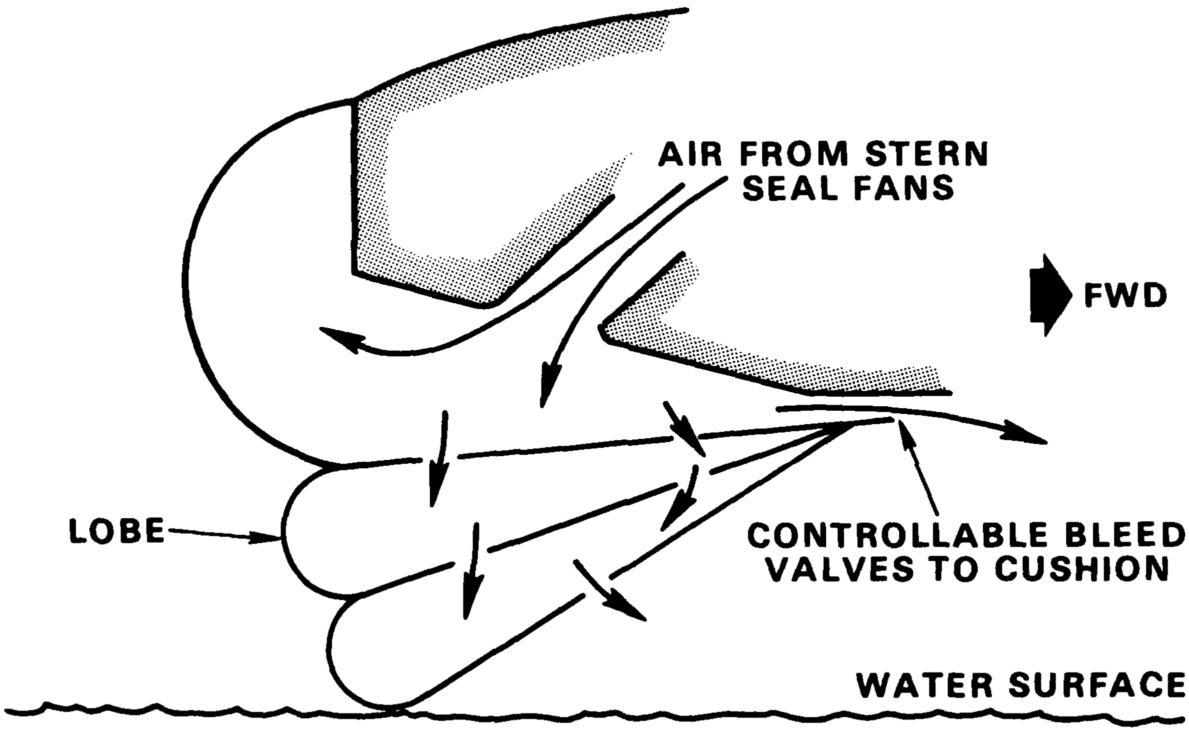


FIGURE 1. STERN SEAL SCHEMATIC

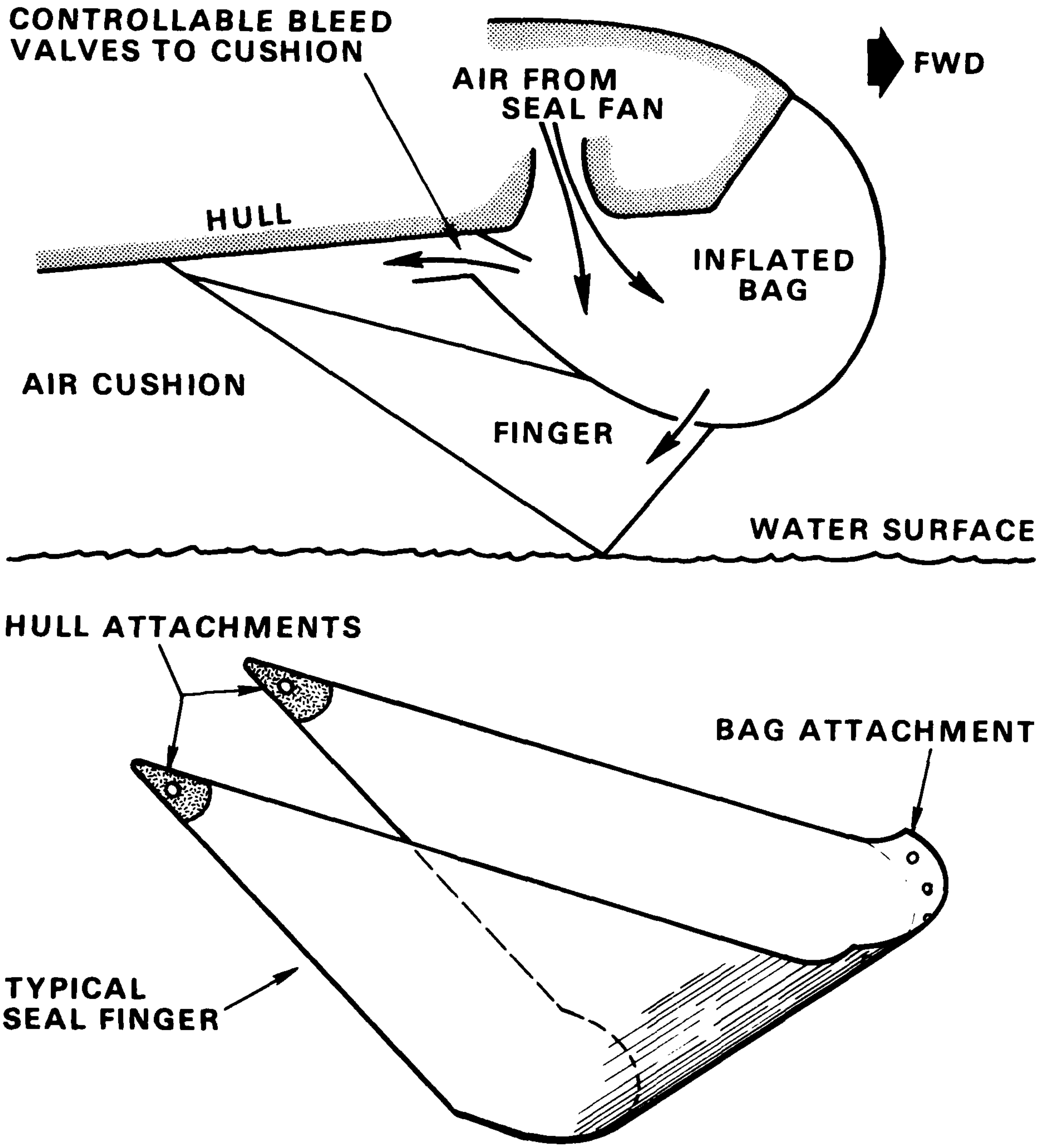
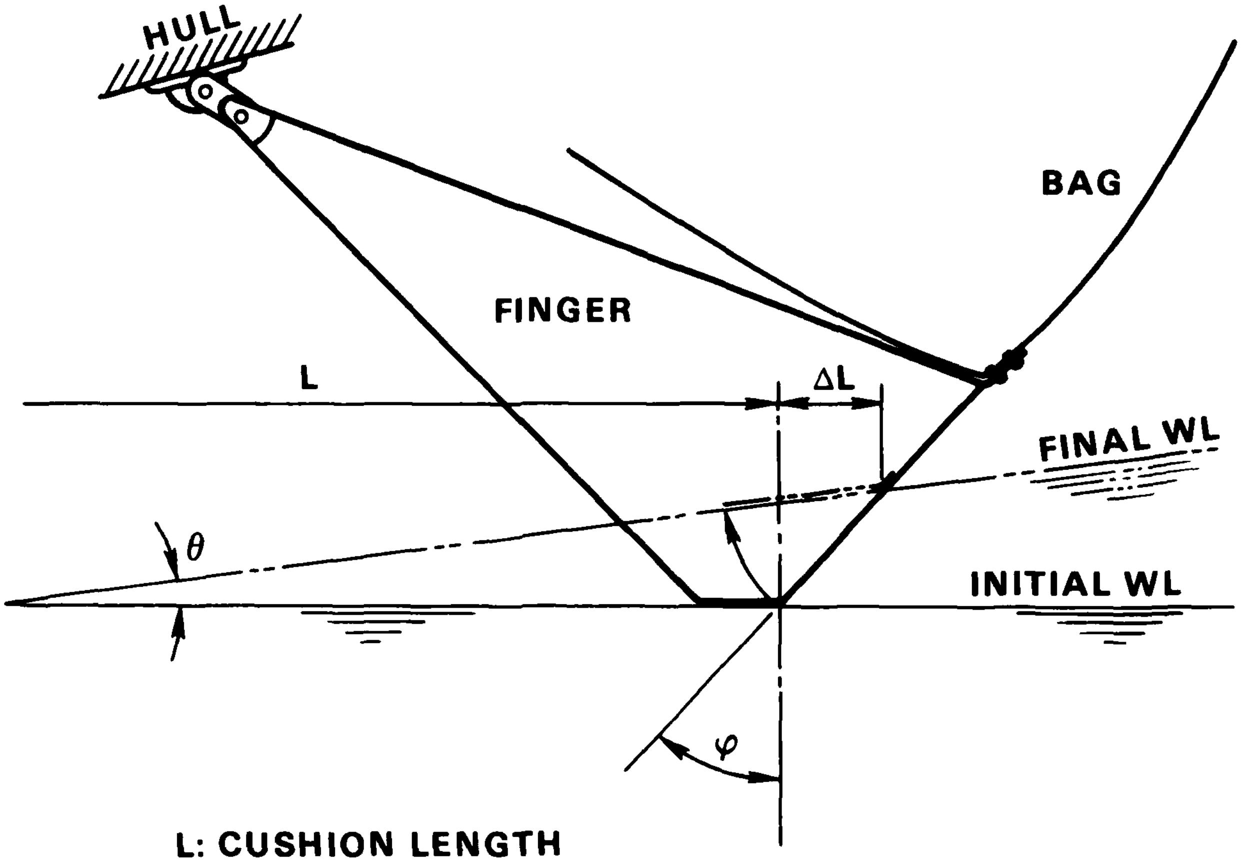


FIGURE 2. BOW SEAL SCHEMATIC



L: CUSHION LENGTH

ΔL: INCREASE IN L CAUSED BY BUCKLED FINGERS

φ: RAKE ANGLE (FROM VERTICAL)

θ: DOWN TRIM ANGLE

FIGURE 3. SEAL FINGERS-PITCH RESTORING MECHANISM

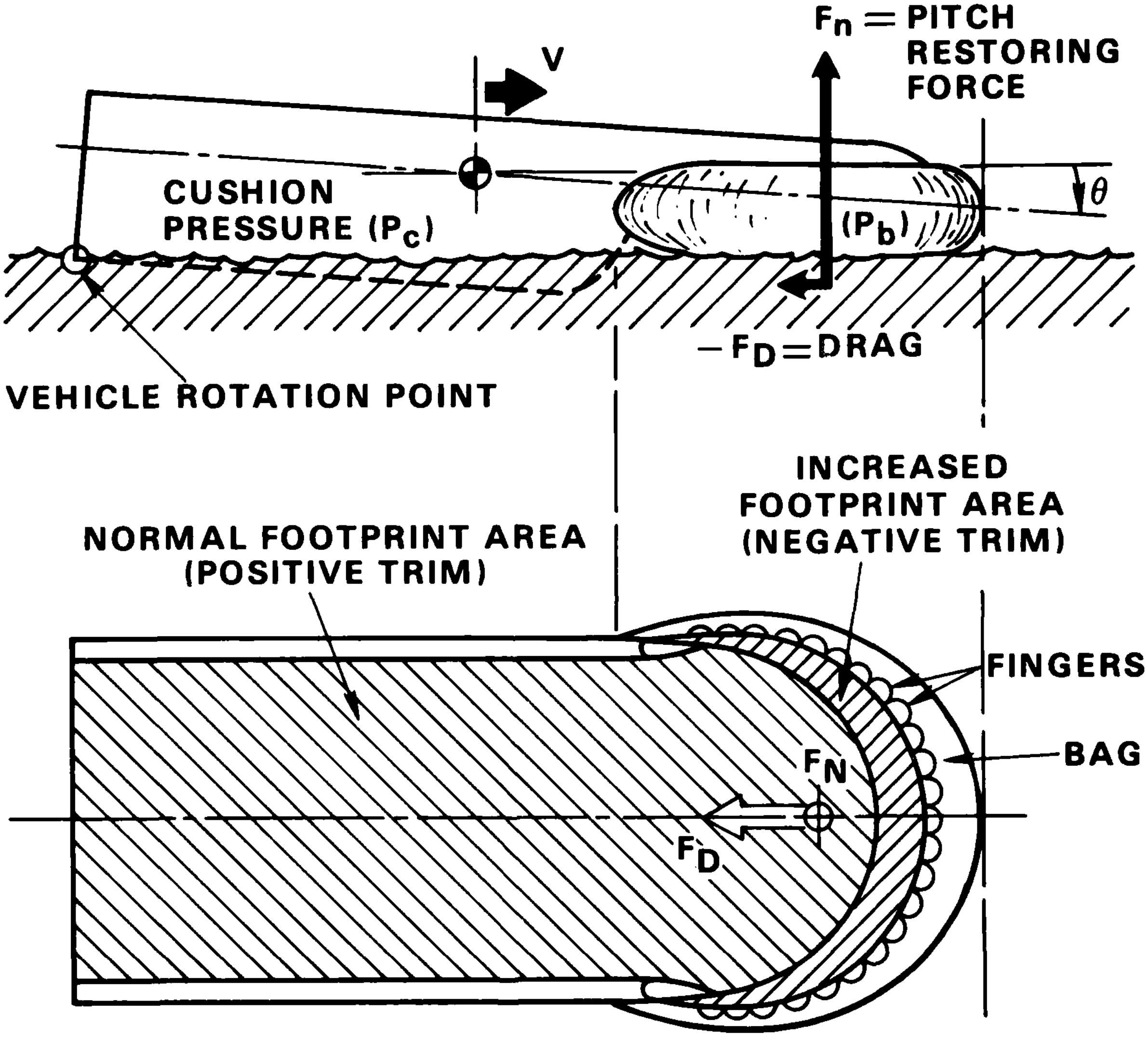


FIGURE 4. CUSHION LENGTH VARIATIONS WITH TRIM CHANGE

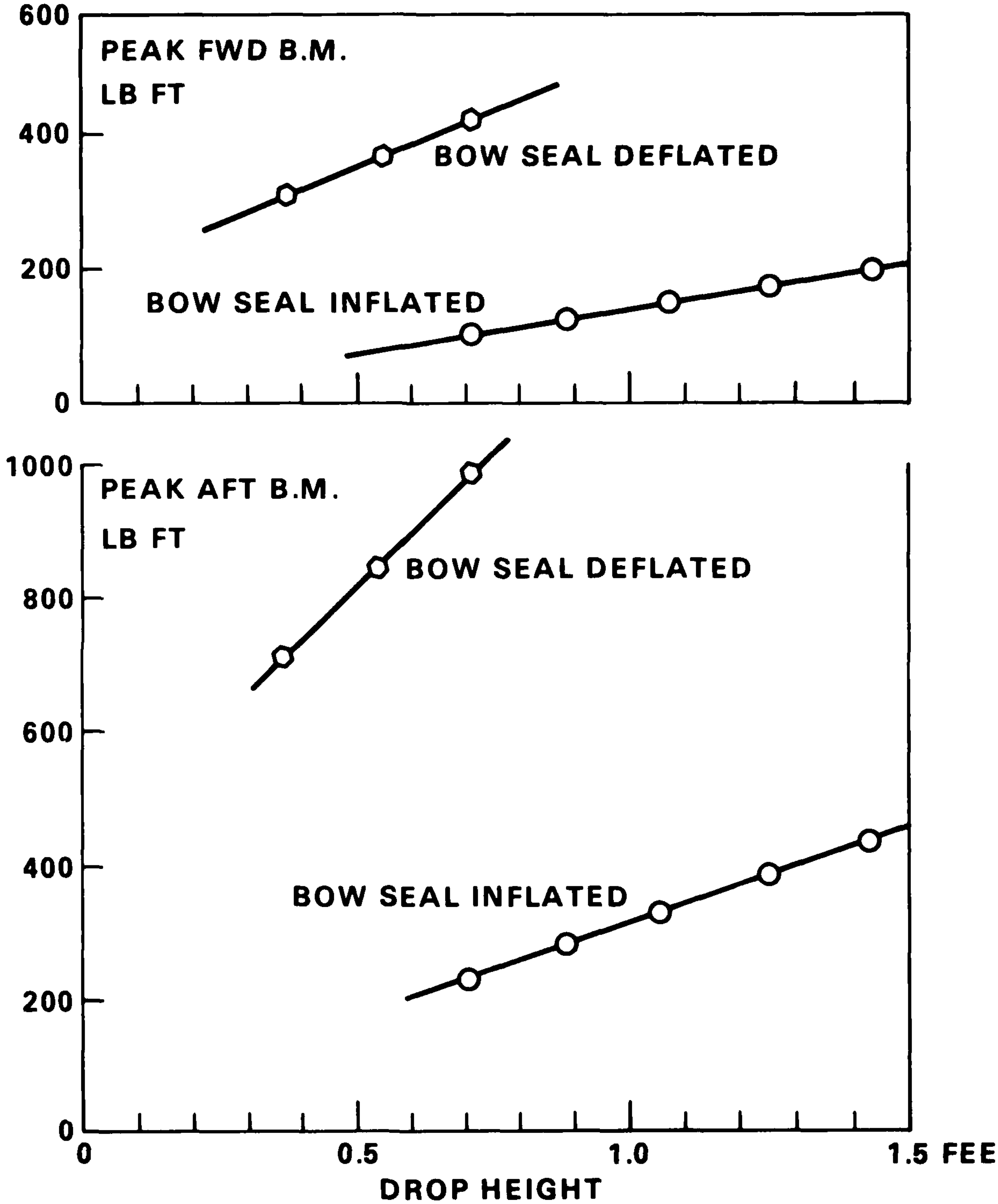


FIGURE 5. EFFECT OF BOW SEAL ON LOADS

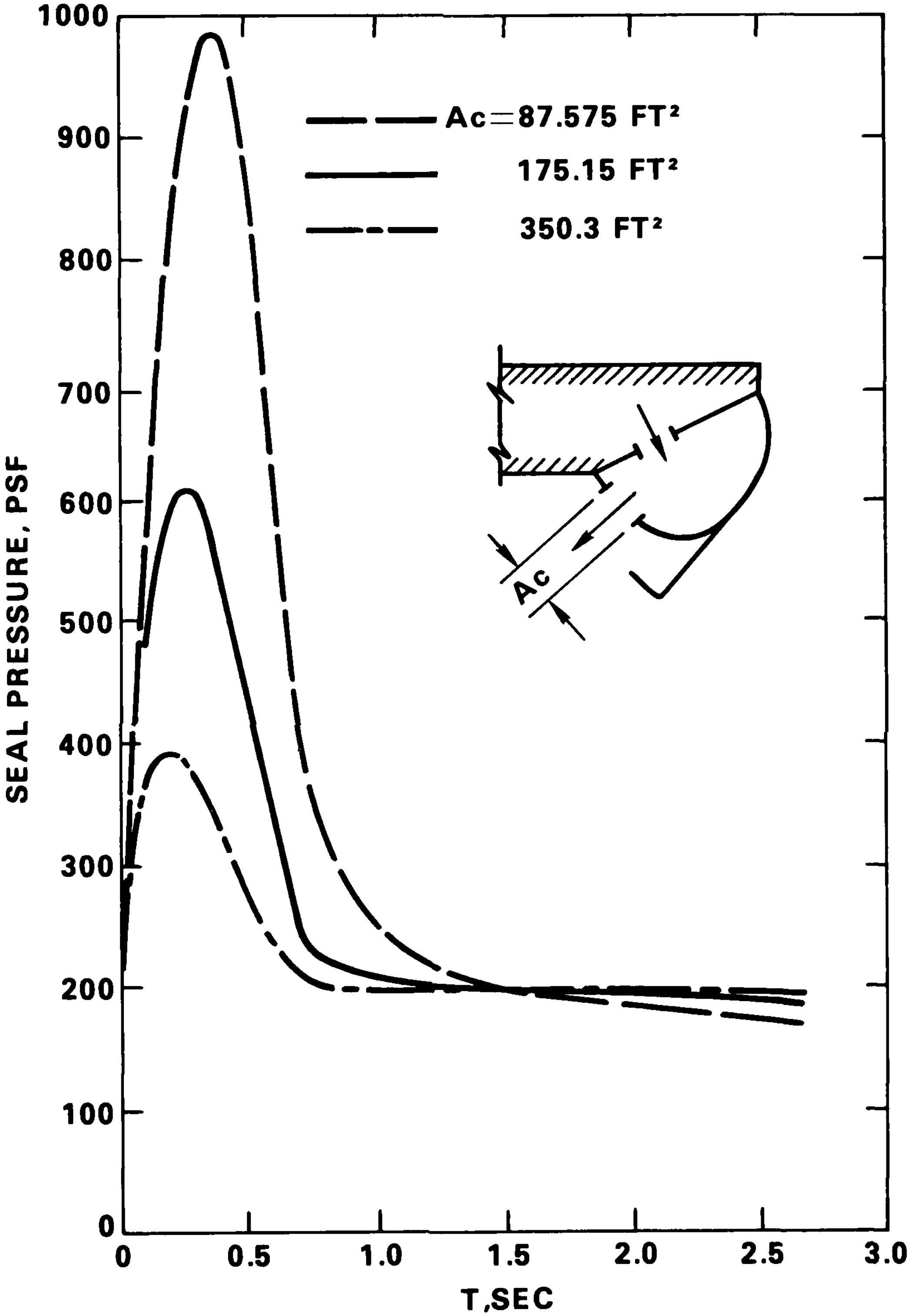


FIGURE 6. EFFECT OF OPENING AREA ON BAG PRESSURES DURING SLAMMING

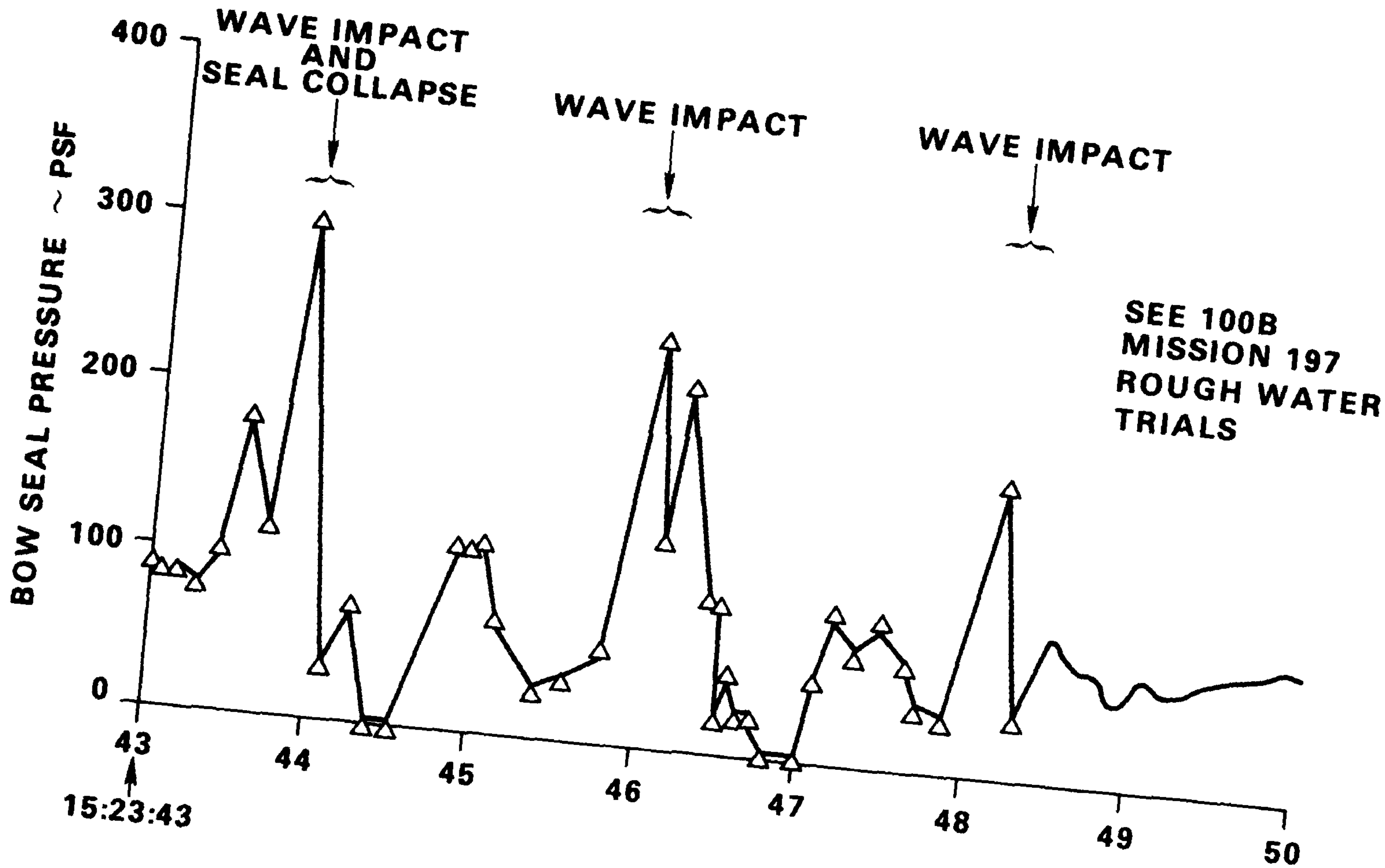


FIGURE 7. SES 100B BOW SEAL PRESSURE TIME HISTORY

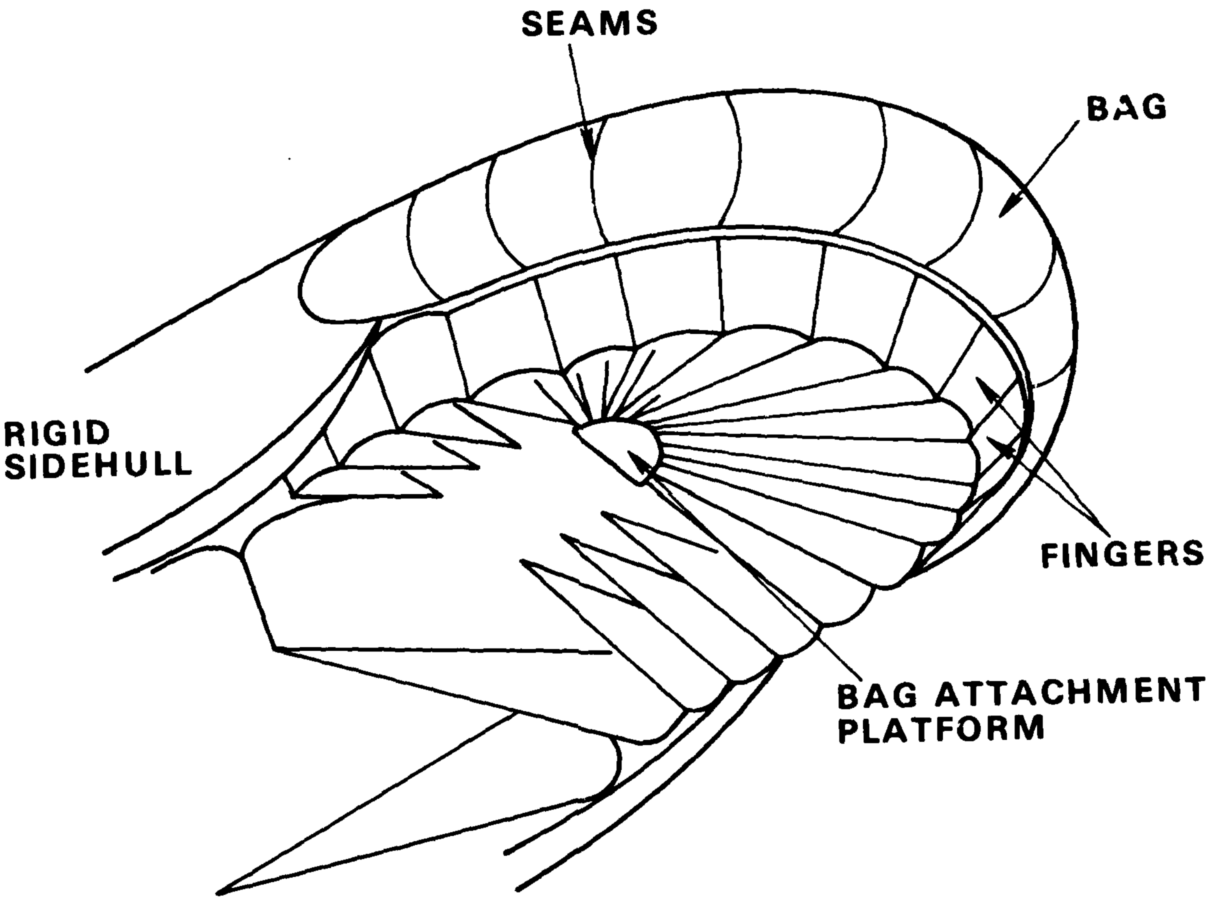
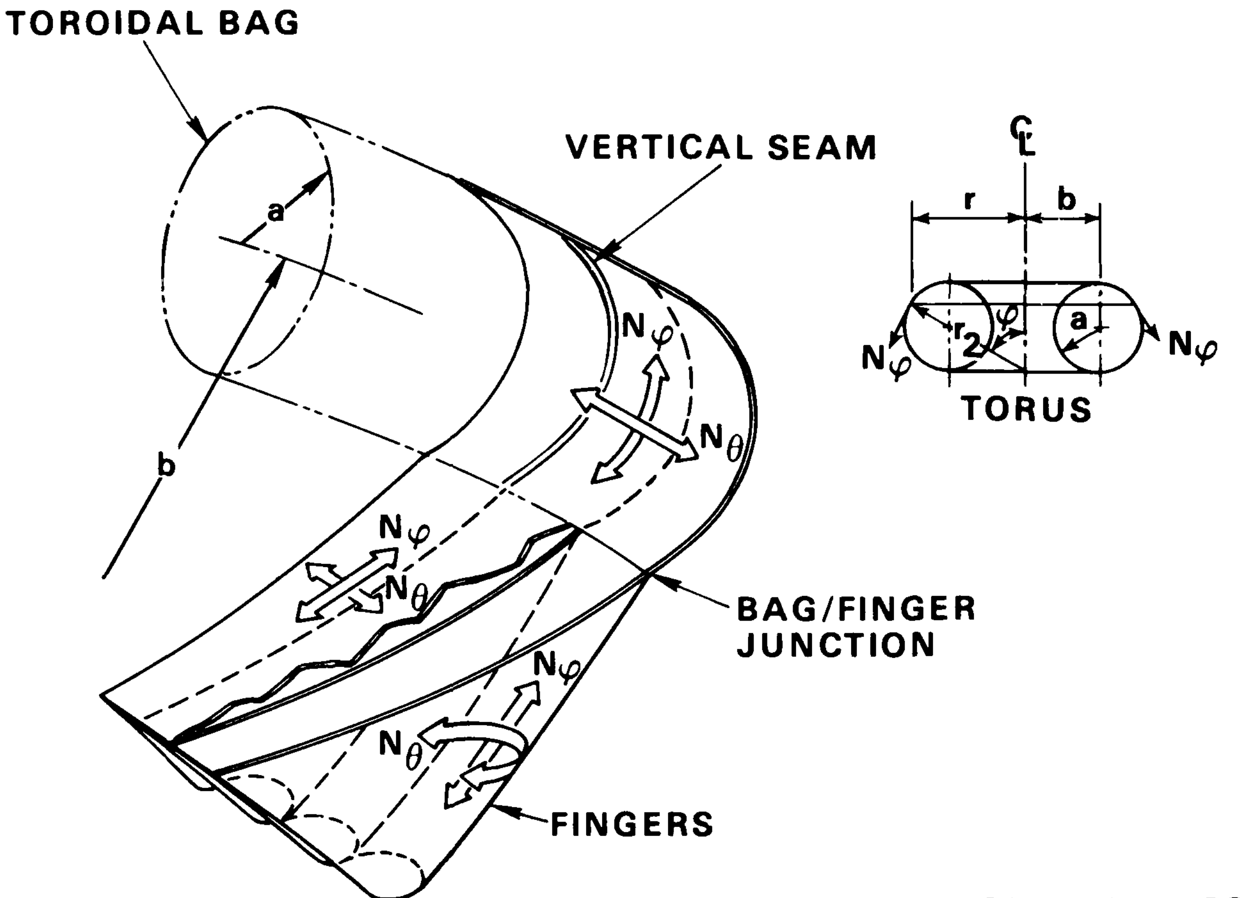


FIGURE 8. 2KSES BOW SEAL ("3 D" SEAL ARRANGEMENT)



N_θ: MERIDIONAL STRESS

N_φ: HOOP STRESS

FIGURE 9. PRINCIPAL STRESS DIRECTIONS IN A TYPICAL BAG AND FINGER SEAL SYSTEM

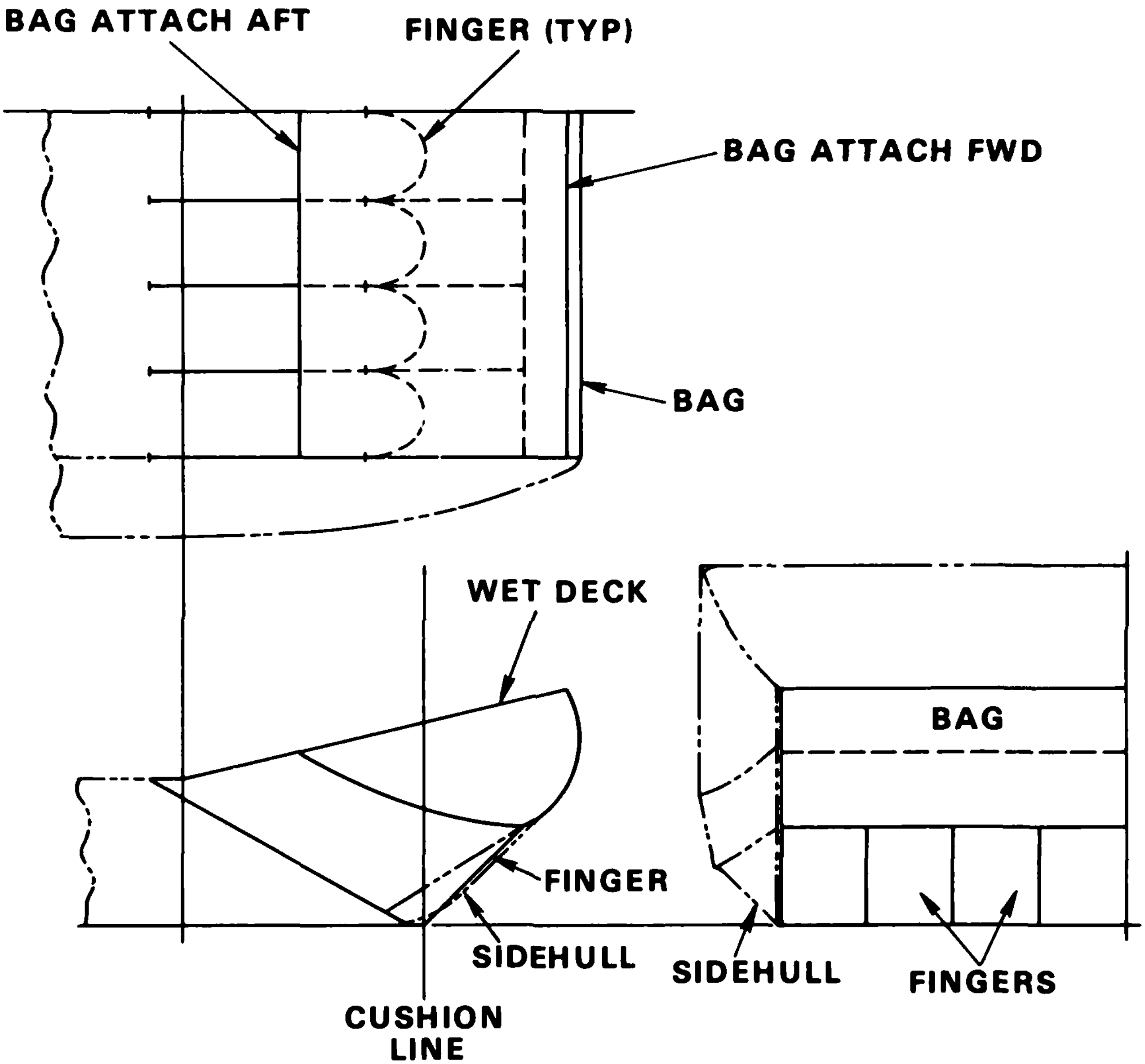


FIGURE 10. "2 D" – SINGLE-MEMBRANE SES BOW SEAL
(EXTENDED SIDEHULLS)

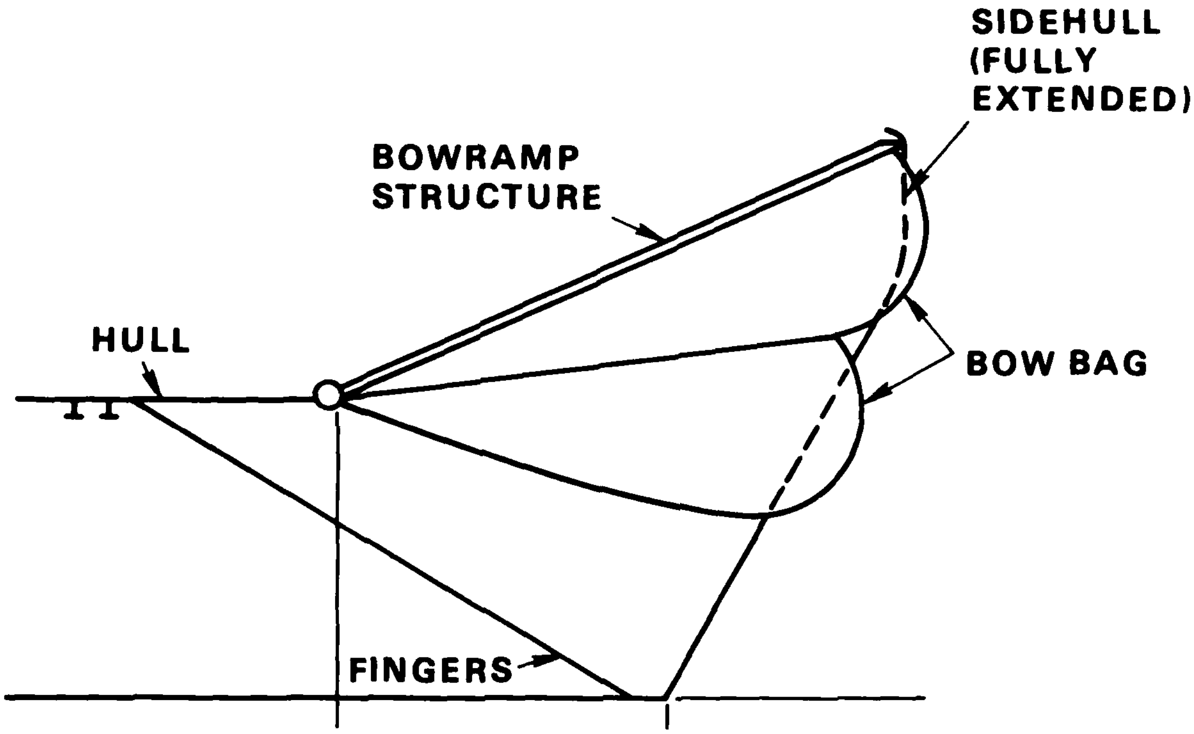


FIGURE 11. MULTI-LOOP "2 D" BAG FOR LARGE SES

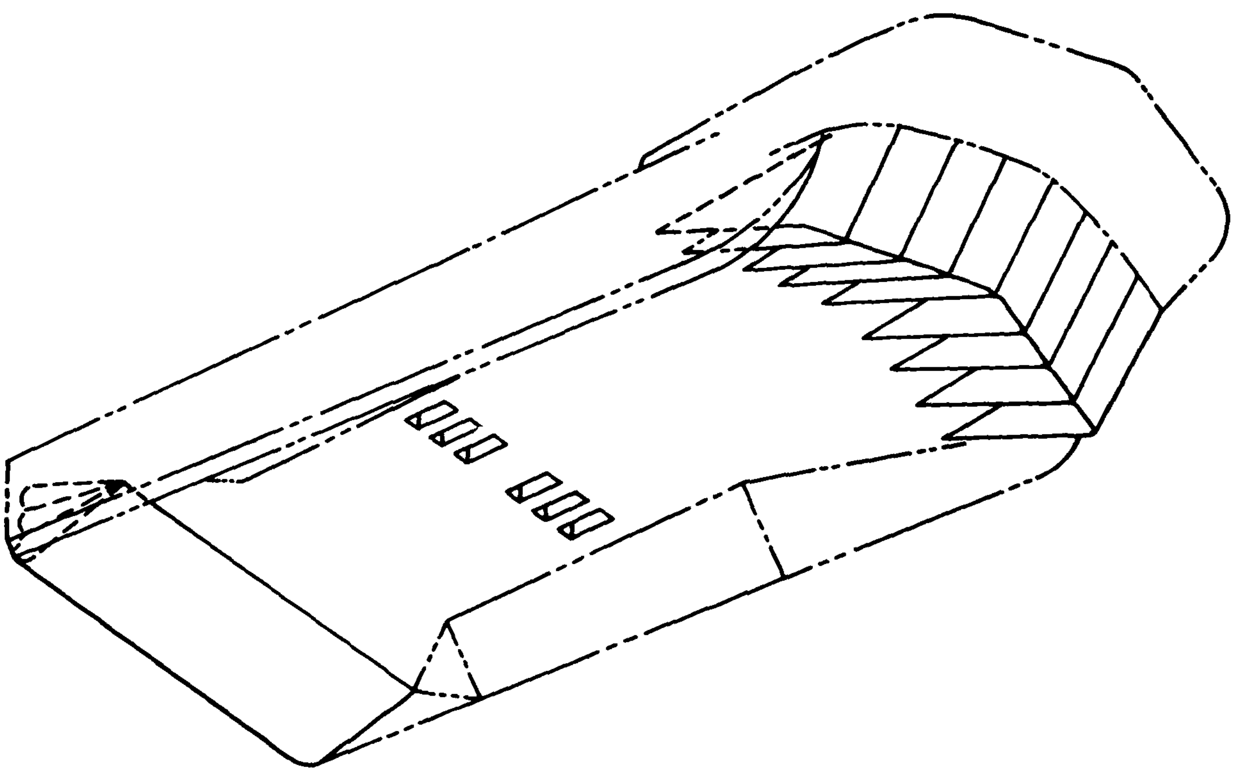


FIGURE 12. SES 110 FINGER BOW SEAL

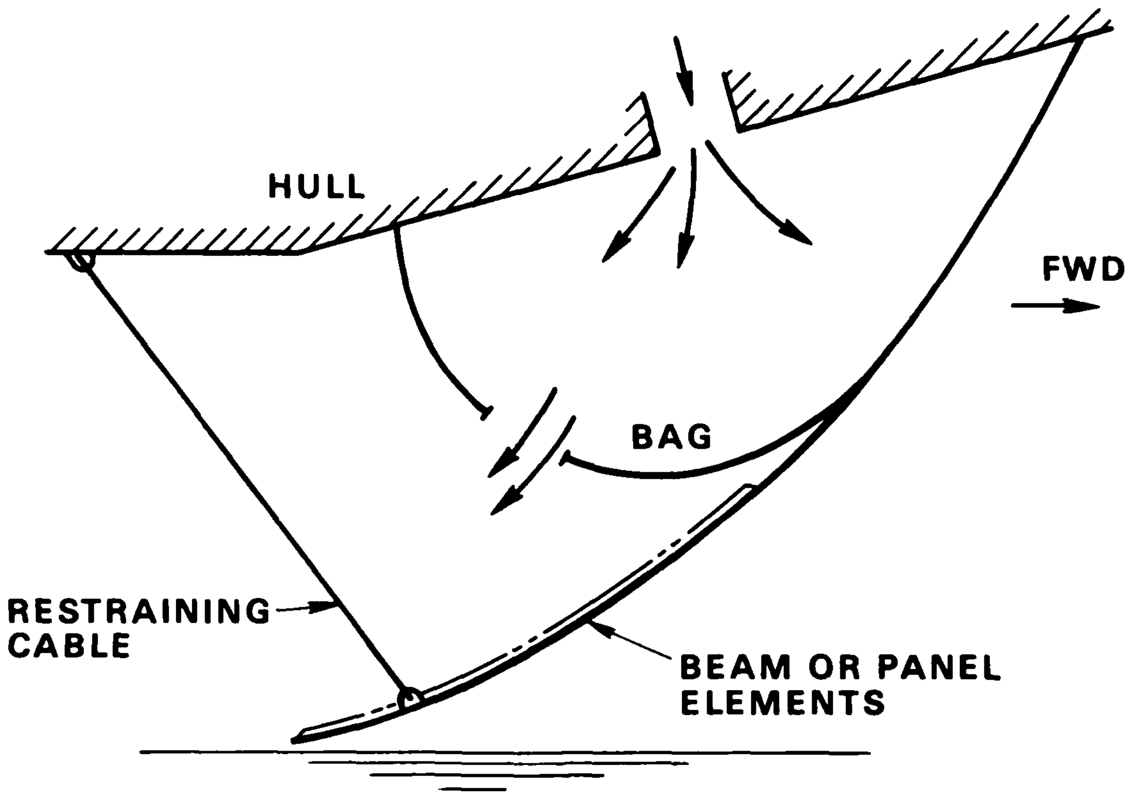


FIGURE 13. SCHEMATIC OF A SEMI-FLEXIBLE SEAL

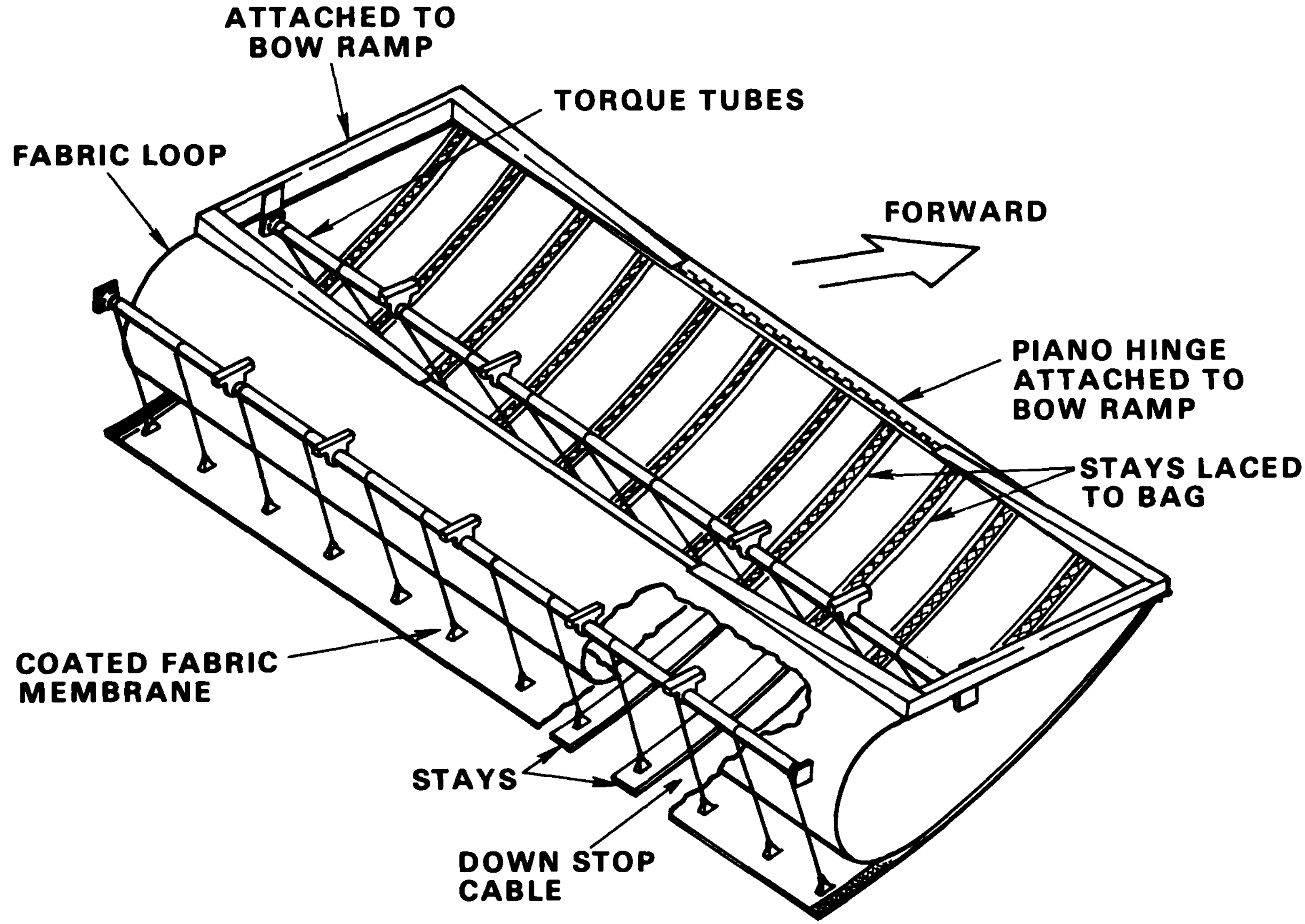


FIGURE 14. STAY STIFFENED FABRIC MEMBRANE SEAL

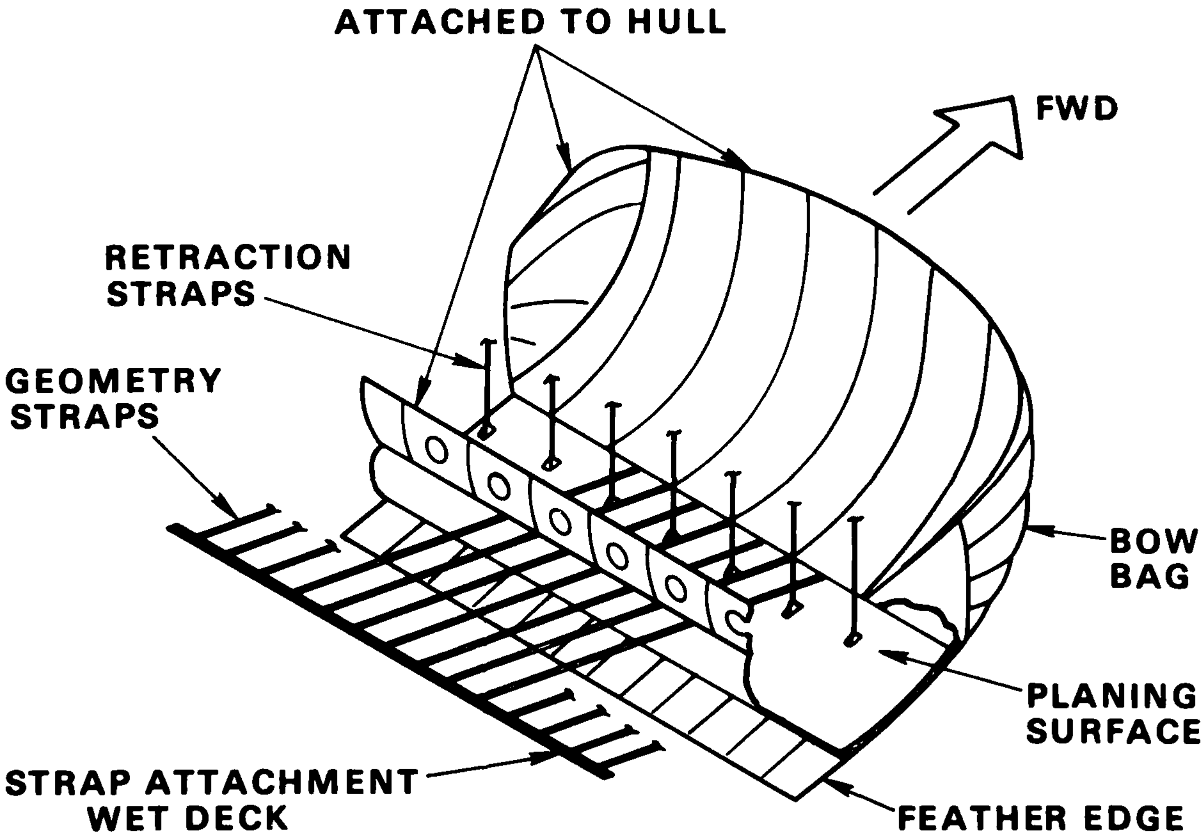


FIGURE 15. SINGLE PLANER BOW SEAL

FIGURE 16. SINGLE PLANER SEAL ON XR-ID SES

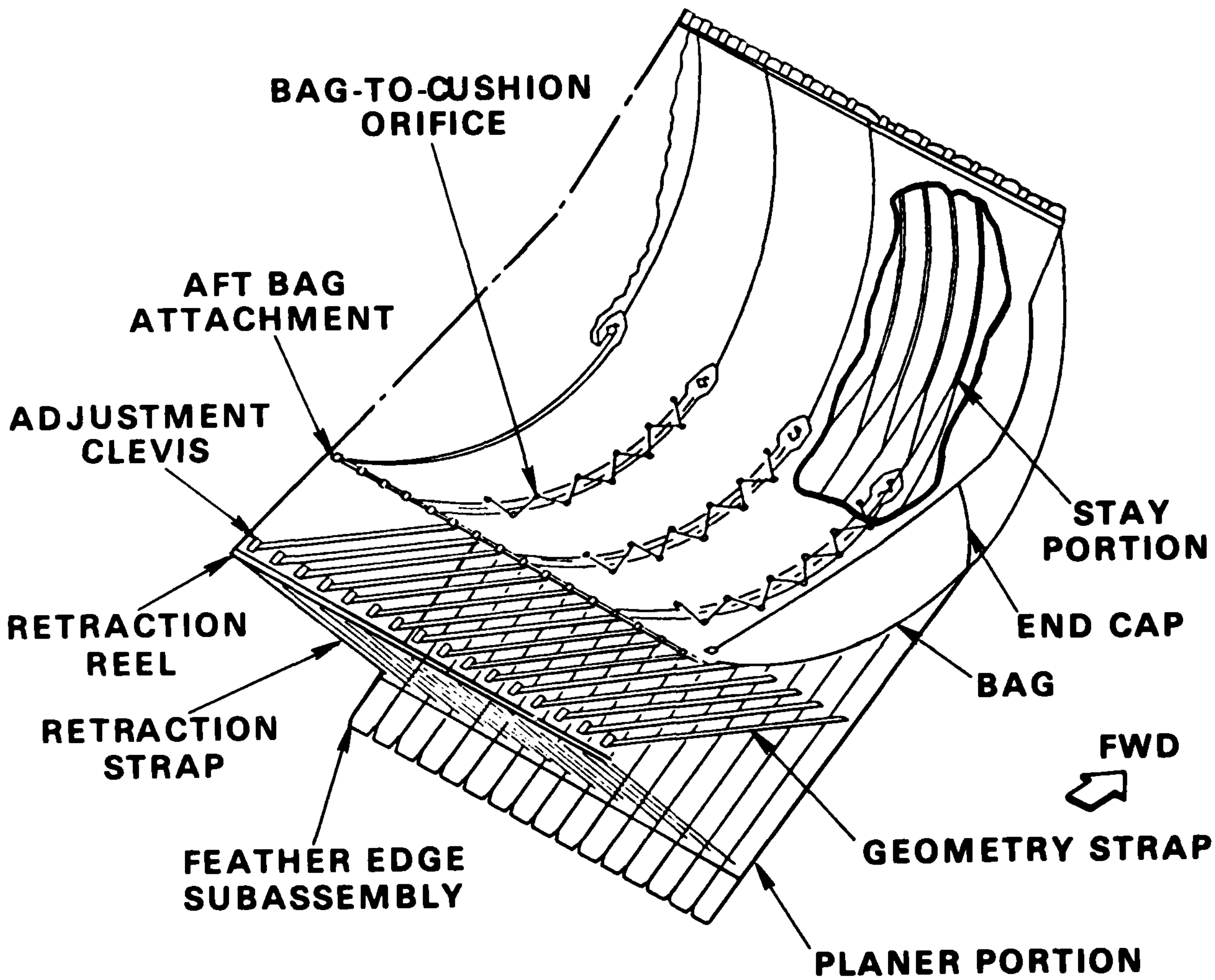


FIGURE 17. PLANING BOW SEAL

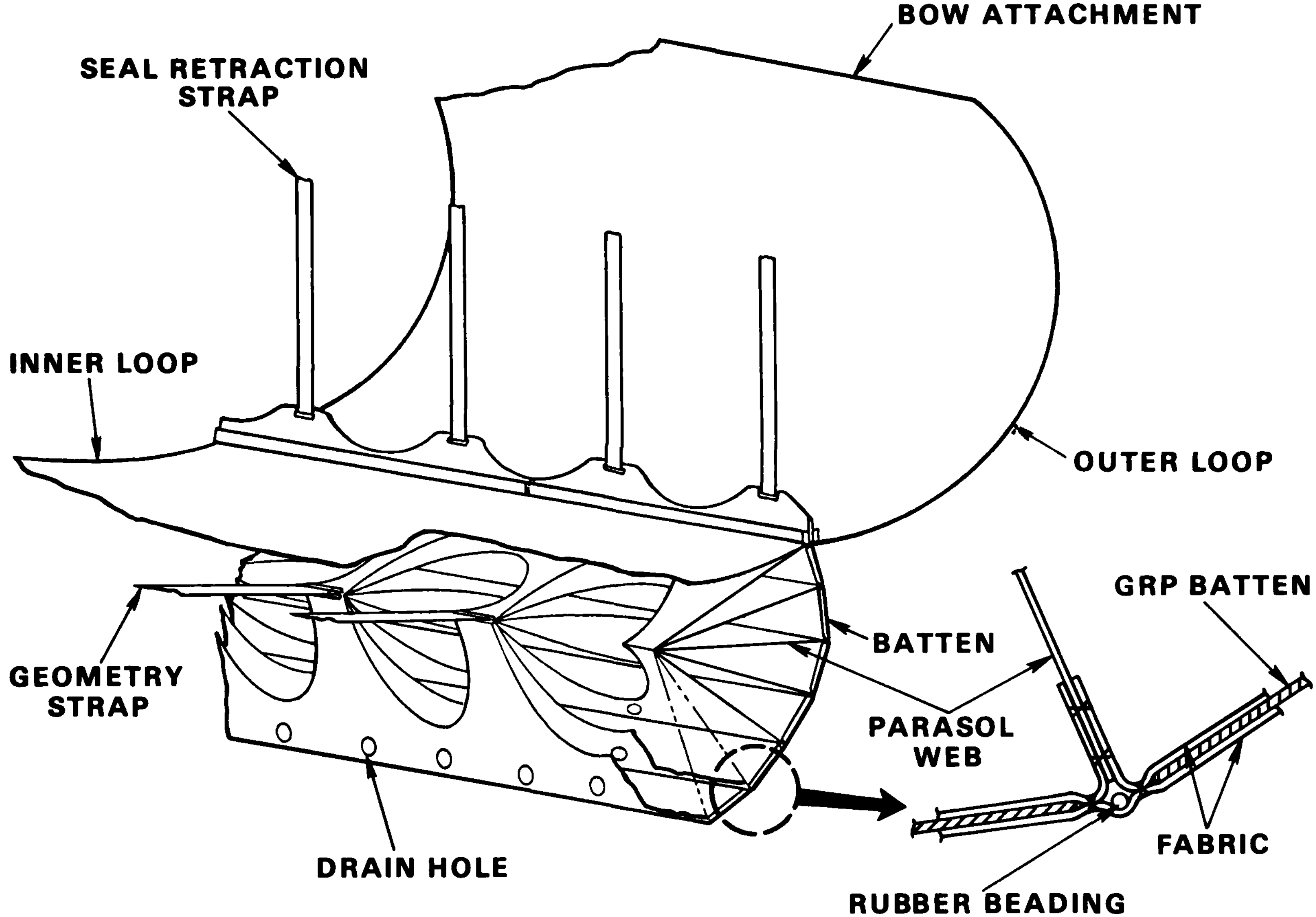


FIGURE 18. TSM SEAL CONCEPT

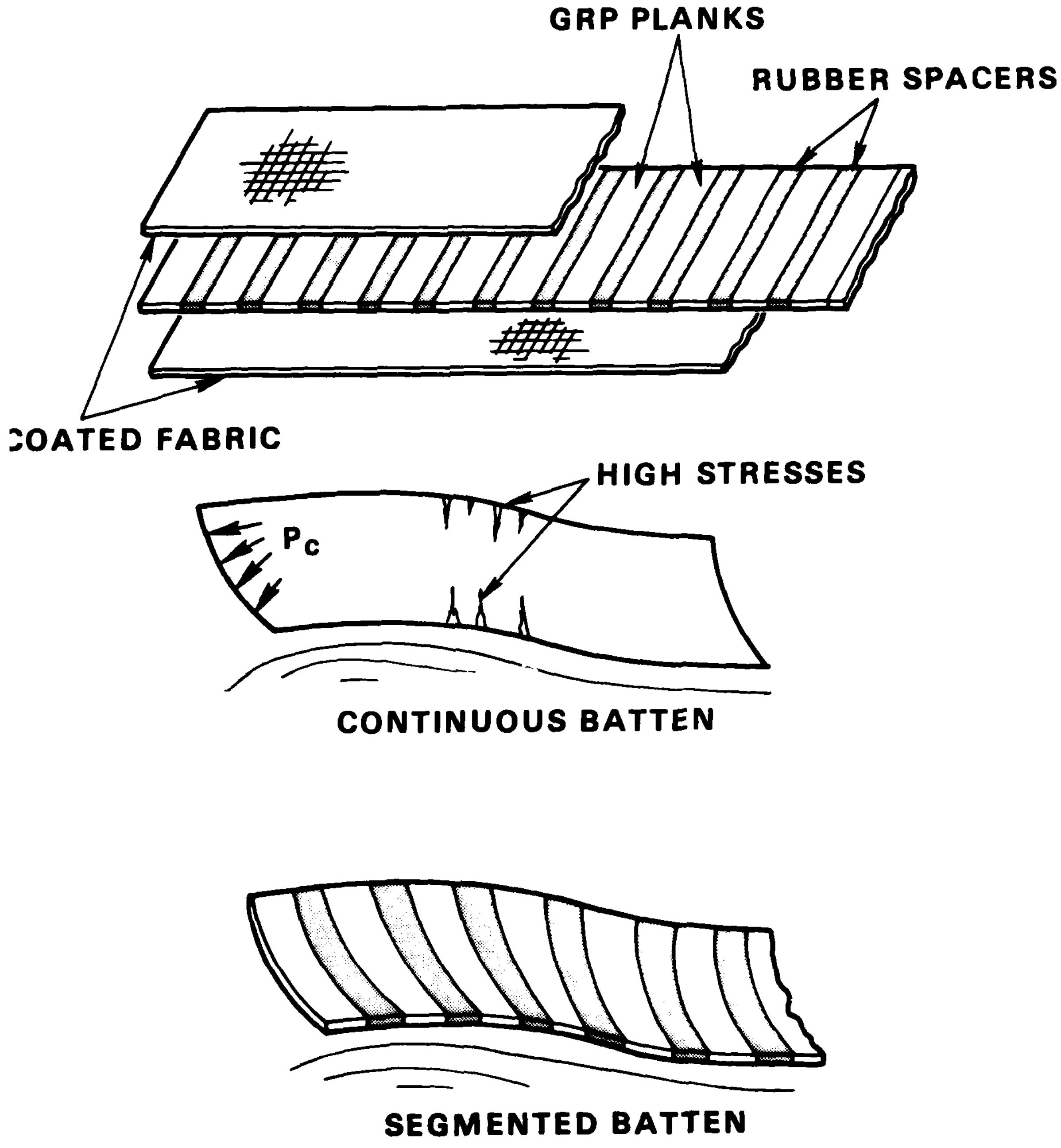


FIGURE 19. SEGMENTED VS. CONTINUOUS BATTENS

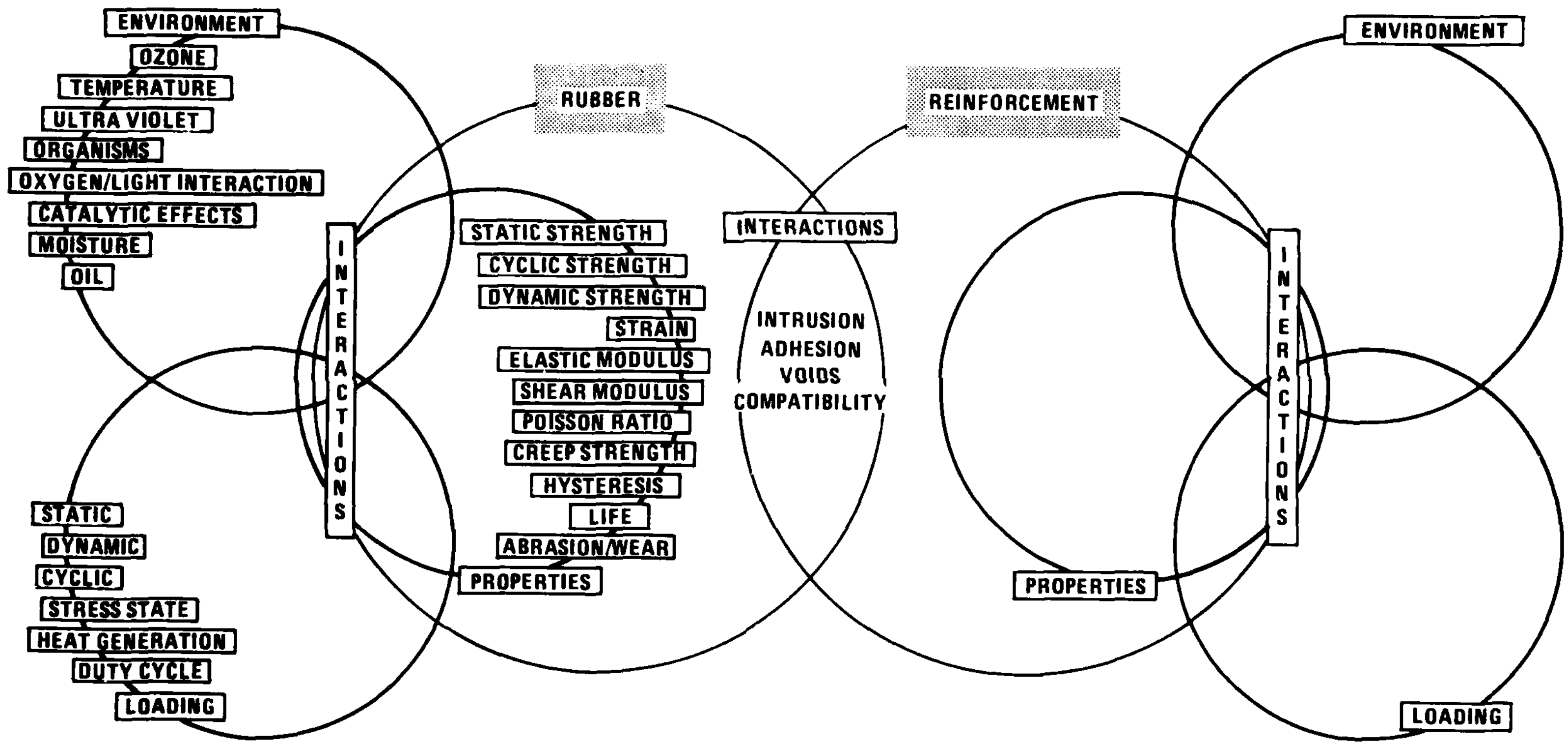


FIGURE 20. FACTORS THAT INFLUENCE THE PERFORMANCE OF SEAL MATERIALS

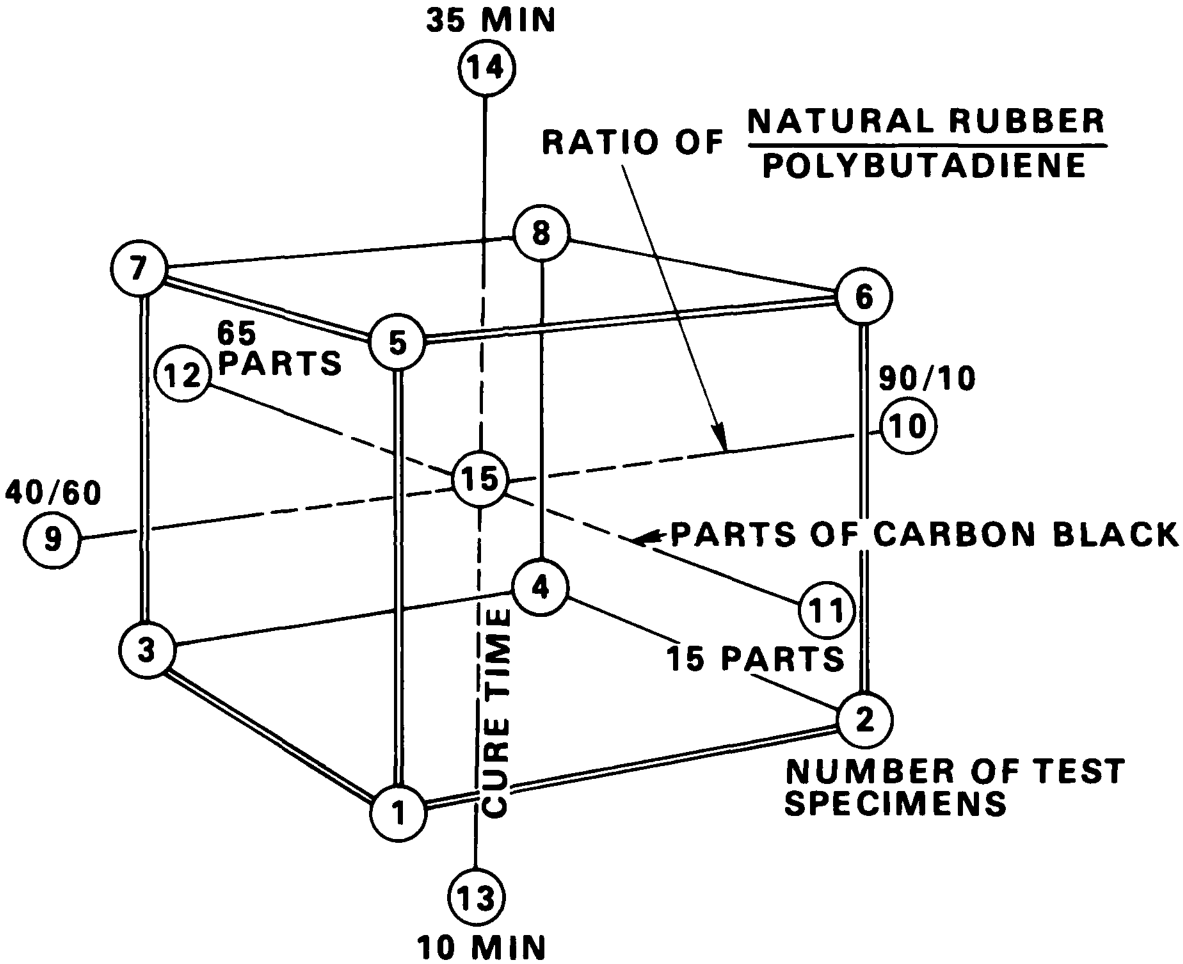


FIGURE 21. TYPICAL RANGE OF ELASTOMER VARIABLES TESTED AT GOODYEAR

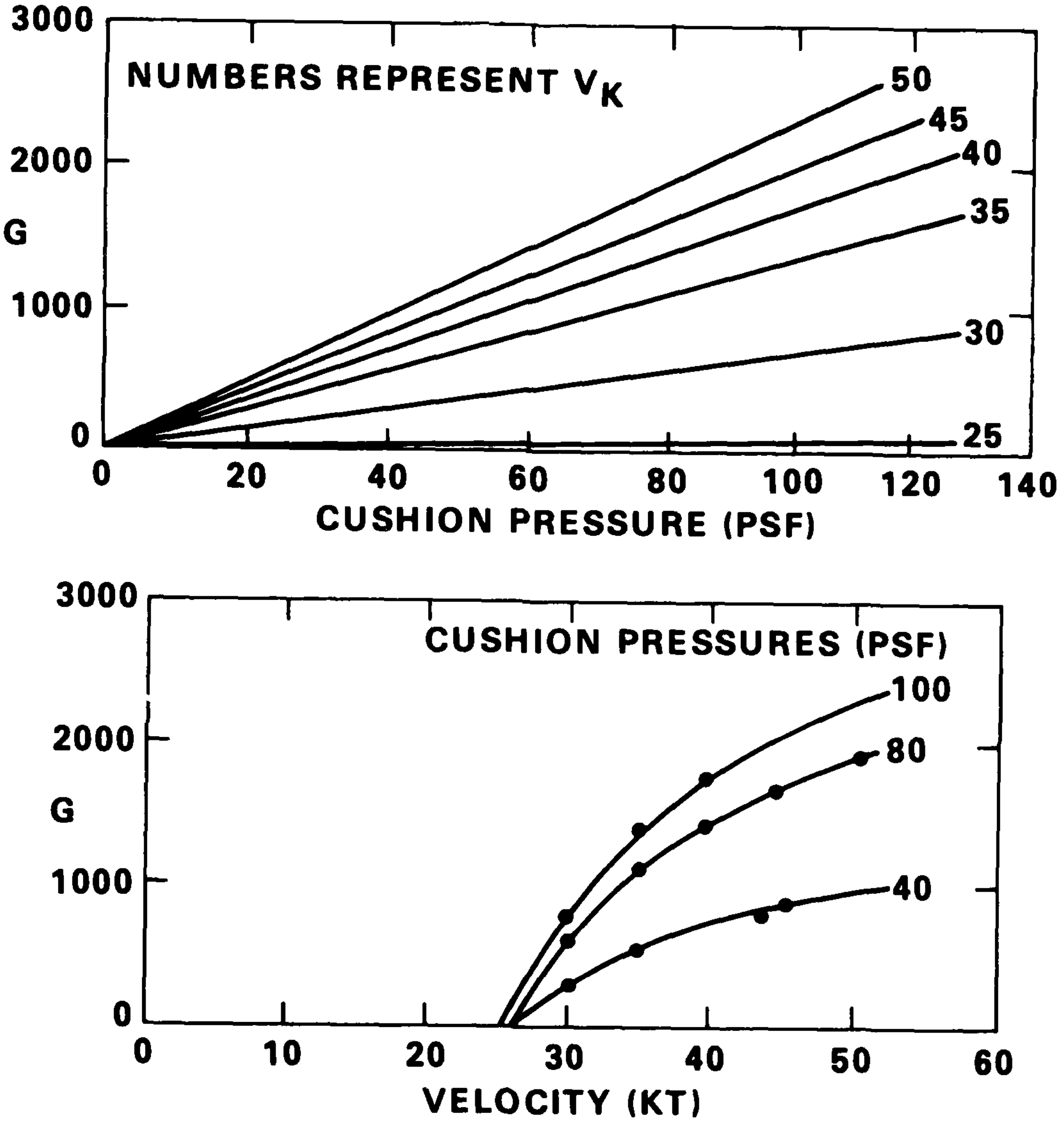


FIGURE 22. FINGER ACCELERATIONS VS. SPEED & PRESSURE

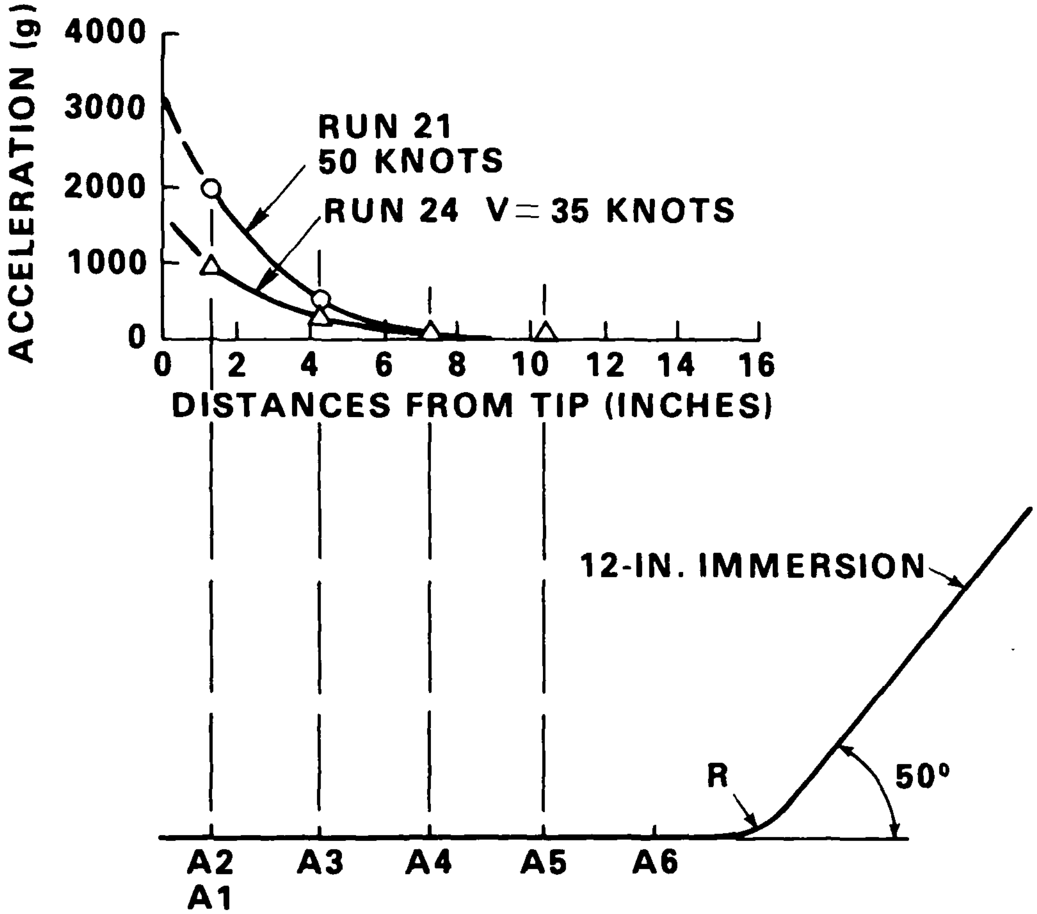


FIGURE 23. ACCELERATION AMPLITUDE VS. DISTANCE FROM FINGER TIP